

Nuclei in the Cosmos School • 2025

STELLAR EVOLUTION

Alessandro Chieffi INAF, Italy



Solar chemical composition





The temperature in the inner core of a star increases only as a consequence of the gravitational contraction

According to the Virial theorem, a fraction of the energy gained by the contraction leads to the increase of the temperature while the remaining part is lost outward (the Luminosity)

$$\mathbf{Log}(\mathbf{T}) \propto \mathbf{Log}(\mu^{\mathbf{3}}\mathbf{M^{2}}) + \frac{1}{\mathbf{3}}\mathbf{Log}(\rho)$$

Hydrostatic equilibrium + EOS (Perfect Gas + radiation)

$$\left[{\rm L} \propto {\rm M}^3 \right]$$

+ radiative equilibrium (valid in self regulating conditions)















	0 14	1 14	2 14	3 14	4 14	5 14	6 14	7 14	8 14	9 14	10 14	11 14	12 14	13 14	14 14	15 14
	¹⁴ Si	¹⁵ Si	¹⁶ Si	¹⁷ Si	¹⁸ Si	¹⁹ Si	²⁰ Si	²¹ Si	²² Si	²³ Si	²⁴ Si	²⁵ Si	²⁶ Si	²⁷ Si	²⁸ Si	²⁹ Si
	0 13	1 13	2 13	3 13	4 13	5 13	6 13	7 13	8 13	9 13	10 13	11 13	12 13	13 13	13	15 13
	¹³ Al	¹⁴ Al	¹⁵ Al	¹⁰Al	¹ 'Al	¹⁸ Al	¹⁹ Al	²⁰ Al	²¹ Al	²² Al	²³ Al	²⁴ Al	²⁵ A1	²⁶ A	Ϋ́́ΑΙ	²⁸ Al
	0 12	1 12	2 12	3 12	4 12	5 12	6 12	7 12	8 12	9 12	10 12	12	12 12	12	12	15 12
	'²Mg	^{'°} Mg	'"Mg	^{1°} Mg	'°Mg	''Mg	'°Mg	^{'®} Mg	NeN	laMgAl	55 MK	24Ng		²⁰Mg	²⁰Mg	²′Mg
	0 11	1 11	2 11	3 11	11 4 11 5		6 11	7 11	8 11 10	9 11 20	10 11	11	12 11	Ne	NaMa	
	''Na	'²Na	'°Na	'"Na	¹⁹ Na	'⁰Na	''Na	'°Na	^{'®} Na	²⁰Na	²'Na	²² Na	Na			<mark>,</mark>
	0 10	1 10	2 10	3 10	4 10	5 10	6 10	7 10	8 10	9 10	10 10	10	10	13 10	14 10	15 10
	"Ne	''Ne	^{'2} Ne	^{1°} Ne	' ^₄ Ne	'°Ne	'°Ne	''Ne	'°Ne	^{'®} Ne	²⁰ Ne	²'Ne	²² Ne	²³ Ne	²⁴Ne	^{2°} Ne
	0 9	1 9	2 9	3 9	4 9	5 9	6 9	7 9	8 9	9 9	10 9	11 9	12 9	13 9	14 9	15 9
	۴F	۳F	''F	'²F	¹³ F	'⁴F	'°F	"F	''F	'°F	¹⁹ F	²⁰ F	²'F	²² F	²³ F	²⁴ F
	0 8	1 8	2 8	3 8	CN	0 25-3	30 MK	8	8 8	8	10 8	11 8	12 8	13 8	14 8	15 8
	°0	°٥	100	110	U	0	U		160	.0	¹⁸ O	¹⁹ O	200	²¹ 0	220	230
	0 7	1 7	2 7	3 7	4 7	5 7	6 7	7 7	7	97	10 7	11 7	12 7	13 7	14 7	15 7
	ΎΝ	۴N	⁹ N		25 MK		¹³ N	I ⁴ N	Ň		N-ON	cycle		²⁰ N	²¹ N	²² N
	0 6	1 6	2				6 6	6	8 6 9				6	13 6		15 6
	°C	′C	°C	°C	°C	°C	¹² C	ъС	¹⁴C	¹⁵C	™C	1′C	¹⁸ C	¹⁹ C	²⁰ C	²¹ C
	0 5	1 5	2 5	3 5	4 5	5 5	6 5	7 5	8 5	9 5	10 5	11 5	12 5	13 5	14 5	15 5
	°В	°В	′В	°В	°В	™B	"B	¹² B	¹³ B	¹⁴ B	™B	™B	¹ ′B	ı®В	¹⁹ В	²⁰ B
	0 4	1 4	2 4	3 4	4 4	5 4	6 4	7 4	8 4	9 4	10 4	11 4	12 4	13 4	14 4	15 4
	⁴Be	°Be	°Be	/je	°Ве	*Be	[™] Be	''Be	¹² Be	' [®] Be	l⁴Be	'°Be	"Be	''Be	'°Be	¹⁹ Be
nn 10 20 M/	3	1 3	2	3 3	3	5 3	6 3	7 3	8 3	9 3	10 3	11 3	12 3	13 3	14 3	15 3
pp 10-20 IVIK		⁴Li	°Ľi	_ °Li	Li	°Li	[°] Li	"Li	''Li	'²Li	¹³ Li	¹⁴ Li	"Li	"Li	''Li	'°Li
	7 2		2 2	3 2	4 2	52	6 2	7 2	8 2	9 2	10 2	11 2	12 2	13 2	14 2	15 2
	² He	³ He	fHe	°Не	P-P	chain		°Не	'⁰He	''He	¹² He	¹³ He	'⁴He	"He	'⁰He	''He
	0 1	1 1	2 1	3 1			1	7 1	8 1	9 1	10 1	11 1	12 1	13 1	14 1	15 1
	'H	² H	ЗН	l⁴H	۶H	۴H	′Η	в	°Н	¹⁰H	"H	¹² H	¹³ H	¹⁴H	¹⁵H	¹⁰H



$$R_{ij} = \frac{y_i y_j}{1 + \delta_{ij}} N_A^2 \rho^2 < \sigma v >_{ij}$$



$$R_{ij} = \frac{y_i y_j}{1 + \delta_{ij}} N_A^2 \rho^2 < \sigma v >_{ij}$$



The P-P chain

$$4p \rightarrow^{4} He \ [26.73 MeV] \qquad E_{H \rightarrow He} = 6.44 \times 10^{18} \ erg \ g^{-1}$$

Energy released by an Earthquake of magnitudo 5 on the Richter scale







$\begin{array}{c} \mathsf{CNO} \ \mathsf{cycle} \\ T\sim 3-5\cdot 10^7 \ \mathrm{K} \quad \rho\sim 1-10 \ \mathrm{gcm}^{-3} \end{array}$





CNO cycle

T > 20 MK $\rho \sim 1 - 10 \text{ [gr cm}^{-3}\text{]}$

 $m ^{14}N(p,\gamma)^{15}O$ slowest reaction (measured by LUNA/LENA)

CNO processed material: ${
m ^{12}C}\downarrow {
m ^{14}N}\uparrow {
m ^{16}O}\downarrow$

Typical equilibrium ratios:



NeNa & MgAI (chains or cycles?)

T > 55 MK



NeNa

 $\frac{23}{1}$ Na $(p, \gamma)^{24}$ Mg

 $^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}$ MgAl $^{26}\mathrm{Mg}(p,\gamma)^{27}\mathrm{Al}$ $^{27}\mathrm{Al}(p,oldsymbol{lpha})^{24}\mathrm{Mg}$

NeNa & MgAI (chains or cycles?)







NeNa & MgAI (chains or cycles?)

T > 55 MK



Fig. 2 Run of abundance ratios for light elements in RGB stars in NGC 2808. O, Na, Si, and Mg are from Carretta (2015), Al and CN abundances from Carretta et al. (2018). The figure is adapted from the invited review by Carretta (2016)

	0 14	1 14	2 14	3 14	4 14	5 14	6 14	7 14	8 14	9 14	10 14	11 14	12 14	13 14	14 14	15 14
	¹⁴ Si	¹⁵Si	¹⁶ Si	¹ ′Si	¹⁸ Si	¹⁹ Si	²⁰ Si	²¹ Si	²² Si	²³ Si	²⁴ Si	²⁵ Si	²⁶ Si	27 S i	²⁸ Si	²⁹ Si
	0 13	1 13	2 13	3 13	4 13	5 13	6 13	7 13	8 13	9 13	10 13	11 13	12 13	13 13	13	15 13
	¹³ Al	¹⁴ Al	¹⁵ Al	¹⁶ Al	¹⁷ Al	¹⁸ Al	¹⁹ Al	²⁰ Al	²¹ Al	²² AI	²³ Al	²⁴ Al	²⁵ A1	²⁶ A	² Al	²⁸ Al
	0 12	1 12	2 12	3 12	4 12	5 12	6 12	7 12	8 12	9 12	10 12	12	12 12	12	12	15 12
	¹² Mg	¹³ Mg	¹⁴ Mg	¹⁵ Mg	[™] Mg [™] Mg [™] Mg			¹⁹ Mg	NeN	laMgAl	55 MK		²⁴ Ng	²⁵ Mg	²⁶ Mg	²⁷ Mg
	0 11	1 11	2 11	3 11	4 11	5 11	6 11	7 11	8 11	9 11	10 11	11	12 11	13 11	14 11	15 11
	¹¹ Na	¹² Na	¹³ Na	¹⁴Na	¹⁵Na	¹⁶ Na	¹⁷ Na	¹⁸ Na	¹⁹ Na	²⁰ Na	²¹ Na	²² Na	²² Na	²⁴ Na	²⁵ Na	²⁶ Na
	0 10	1 10	2 10	3 10	4 10	5 10	6 10	7 10	8 10	9 10	10 10	10	10	13 10	14 10	15 10
	¹⁰ Ne	¹¹ Ne	¹² Ne	¹³ Ne	¹⁴ Ne	¹⁵ Ne	¹⁶ Ne	¹⁷ Ne	¹⁸ Ne	¹⁹ Ne	²⁰ Ne	²¹ Ne	²² Ne	²³ Ne	²⁴ Ne	²⁵ Ne
	0 9	1 9	2 9	3 9	4 9	5 9	6 9	7 9	8 9	9 9	10 9	11 9	12 9	13 9	14 9	15 9
	۶F	¹⁰ F	¹¹ F	¹² F	¹³ F	¹⁴ F	¹⁵ F	¹⁶ F	¹⁷ F	¹⁸ F	¹⁹ F	²⁰ F	²¹ F	²² F	²³ F	²⁴ F
	0 8	1 8	2 8	3 8	CN	0 25-3	30 MK	8	8 8	8		11 8	12 8	13 8	14 8	15 8
	°0	°0	¹⁰ O	¹¹ 0		U	U		¹⁶ C	.0	¹⁸ O	¹⁹ O	²⁰ O	²¹ 0	²² 0	²³ 0
	0 7	1 7	2 7	37	4 7	5 7	6 7	7 7	7	9 7	10 7	11 7	12 7	13 7	14 7	15 7
	⁷ N	⁸ N	⁹ N				¹³ N	¹⁴ N	¹ N	¹⁶ N	¹⁷ N	¹⁸ N	¹⁹ N	²⁰ N	²¹ N	²² N
	0 6	1 6	2			e la constante de la constante	6 6	6	8 6	9 6	10 6	11 6	12 6	13 6	14 6	15 6
	°C	⁷ C	°C	°C	¹⁰ C	C	¹² C	¹³ C	¹⁴ C	¹⁵ C	¹⁶ C	¹⁷ C	¹⁸ C	¹⁹ C	²⁰ C	²¹ C
	0 5	1 5	2 5	3 5	4 5	5 5		7 5	8 5	9 5	10 5	11 5	12 5	13 5	14 5	15 5
	⁵B	⁶ B	⁷ B	⁸ B	°B	¹⁰ B	¹¹ B	¹² B	¹³ B	¹⁴ B	¹⁵ B	¹⁶ B	¹⁷ B	¹⁸ B	¹⁹ B	²⁰ B
	0 4	1 4	2 4	3 4	4 4	5 4	6 4	7 4	8 4	9 4	10 4	11 4	12 4	13 4	14 4	15 4
	⁴Be	⁵Be	⁶ Ве	be	⁸ Be	°Be	¹⁰ Be	¹¹ Be	¹² Be	¹³ Be	¹⁴ Be	¹⁵ Be	¹⁶ Be	¹⁷ Be	¹⁸ Be	¹⁹ Be
10.20		3	2	3 3	3	5 3	6 3	7 3	8 3	9 3	10 3	11 3	12 3	13 3	14 3	15 3
op 10-20		4	۶Ľi	⁶ Li	Li	⁸ Li	°Li	¹⁰ Li	"Li	¹² Li	¹³ Li	¹⁴ Li	¹⁵ Li	¹⁶ Li	¹⁷ Li	¹⁸ Li
	0 2		2 2	3 2	4 2	5 2	6 2	7 2	8 2	9 2	10 2	11 2	12 2	13 2	14 2	15 2
	² He	³ He	⁴Ĥe	⁵He	⁶ Не	⁷ He	⁸ He	°Не	¹⁰ He	¹¹ He	¹² He	¹³ He	¹⁴ He	¹⁵ He	¹⁶ He	¹⁷ He
		1 1	2 1	3 1	4 1	5 1	6 1	7 1	8 1	9 1	10 1	11 1	12 1	13 1	14 1	15 1
	¹ H	² H	³ H	⁴H	⁵H	⁶ H	⁷ H	₿H	[®] H	1ºH	''H	¹² H	¹³ H	¹⁴ H	¹⁵ H	¹⁶ H



Central H exhaustion

monotonic family of stars



















He burning

The key parameter that drives the evolution in He burning is the He core mass and NOT the total mass

Central He burning always occurs in a convective environment

 $3\alpha \rightarrow^{12} C$ $^{12}C(\alpha,\gamma)^{16}O$



mantle

H burning shell

He core

α, ¹⁴Ν convective core
The key parameter that drives the evolution in He burning is the He core mass and NOT the total mass

Central He burning always occurs in a convective environment

 $3\alpha \rightarrow^{12} C$ $^{12}C(\alpha,\gamma)^{16}O$



mantle

H burning shell

He core

The key parameter that drives the evolution in He burning is the He core mass and NOT the total mass

Central He burning always occurs in a convective environment

 $T \sim 1.5 - 3.5 \cdot 10^8 \text{ K} \quad \rho \sim 0.2 - 4 \cdot 10^3 \text{ gcm}^{-3}$ $4 \alpha \rightarrow {}^{16}\text{O} \qquad \Delta M = 4 \times 4.0026 - 15.9949 = 0.015 \text{ MeV} \qquad E_{nuc} = 8.70 \cdot 10^{17} \text{ erg/g}$





H burning shell

He core





The key parameter that drives the evolution in He burning is the He core mass and NOT the total mass

Central He burning always occurs in a convective environment

$T \sim 1.5 - 3.5 \cdot 10^8 \text{ K} \quad \rho \sim 0.2 - 4 \cdot 10^3 \text{ gcm}^{-3}$ $4 \alpha \rightarrow {}^{16}\text{O} \qquad \Delta M = 4 \times 4.0026 - \underline{15.9949} = 0.015 \text{ MeV} \qquad E_{nuc} = 8.70 \cdot 10^{17} \text{ erg/g}$

0 14	1 14	2 14	3 14	4 14	5 14	6 14 20	7 14	8 14	9 14	10 14	11 14 25 - 1	12 14	13 14	14 14	15 14
'*Si	"Si	"Si	''Si	"Si	¹⁹ Si	²⁰ Si	²'Si	²² Si	²⁰ Si	²*Si	²³ Si	²⁰ Si	²'Si	2°Si	^{2®} Si
0 13 ¹³ Al	1 13 ¹⁴ Al	² 13	з 13 ¹⁶ АІ	4 13 ¹⁷ Al	5 13 ¹⁸ Al	6 13 ¹⁹ Al	7 13 20 <mark>Al</mark>	⁸ 13 ²¹ Al	9 13 ²² AI	¹⁰ 13	¹¹ ¹³	¹² 13	¹³ 13	¹⁴ 13 ²⁷ Al	¹⁵ 13
0 12	1 12	2 12	3 12	4 12	5 12	6 12	7 12	8 12	9 12	10 12	11 12	12 12	13 12	14 12	15 12
¹² Mg	¹³ Mg	¹⁴ Mg	¹⁵ Mg	¹⁶ Mg	¹⁷ Mg	¹⁸ Mg	¹⁹ Mg	²⁰ Mg	²¹ Mg	²² Mg	²³ Mg	²⁴ Mg	25 lg	٨g	²⁷ Mg
⁴ N(α,γ)) ¹⁸ F	⁻ (β ⁺) ¹⁸ (Ο(α	,γ) ²	²² N	e(α,	n) ²⁵	⁵ Mg	11 Na	¹² 11 ²³ Na	2 Ja	¹⁴ 11 ²⁵ Na	¹⁵ 11 ²⁶ Na
¹⁰ Ne	¹¹ Ne	¹² Ne	¹³ Ne	¹⁴ Ne	¹⁵ Ne	¹⁶ Ne	¹⁷ Ne	¹⁸ Ne	¹⁹ Ne	²⁰ Ne	¹⁰ ²¹ Ne	12 22.Ne	¹³ 10	¹⁴ 10	¹⁵ 10
0 9 9 - -	1 9 10 	2 9 11 0	3 9 12 -	4 9 13 -	5 9 14 m	6 9 15 	7 9 16 m	8 9 17 -	9 9	10 9 19 - -	11	20 9 21⊏	13 9 22 -	14 9 23 m	15 9 24m
								I IF				-1			
° °	90	² 8	³ ⁸	4 8 ¹² 0	⁵ 8	^{6 8}	7 8 ¹⁵ 0	* • 0	9 8 4 ¹⁷ 0	¹⁸ O	¹¹ 8	¹² 8	¹³ 8	¹⁴ 8	¹⁵ 8
0 7	1 7	2 7	3 7	4 7	5 7	6 7		8 7	9 7	10 7	11 7	12 7	13 7	14 7	15 7
⁷ N	⁸ N	⁹ N	¹⁰ N	¹¹ N	¹² N	¹³ N	\smile	¹⁵ N	¹⁶ N	¹⁷ N	¹⁸ N	¹⁹ N	²⁰ N	²¹ N	²² N
о 6 ⁶ С	1 6 7C	2 6 ⁸ C	^{з 6}	4 6 ¹⁰ C	5 6 ¹¹ C	6 6 ¹² C	7 6 ¹³ C	⁸ 6	9 6 ¹⁵ C	¹⁰ 6	¹¹ 6	¹² 6	¹³ 6	¹⁴ 6 20C	^{15 6} ²¹ C
0 5	1 5	2 5	3 5	4 5	5 5	6 5	7 5	8 5	9 5	10 5	11 5	12 5	13 5	14 5	15 5
⁵B	⁶ В	⁷ B	⁸ В	°В	¹⁰ B	¹¹ B	¹² B	¹³ B	¹⁴ B	¹⁵ B	¹⁶ B	¹⁷ B	¹⁸ B	¹⁹ B	²⁰ B
0 4	1 4	2 4	3 4	4 4	5 4	6 4	7 4	8 4	9 4	10 4	11 4	12 4	13 4	14 4	15 4
⁴Be	⁵Be	⁶ Be	⁷ Be	°Ве	°Be	¹⁰ Be	¹¹ Be	¹² Be	¹³ Be	¹⁴ Be	¹⁵ Be	¹⁶ Be	¹⁷ Be	¹⁸ Be	¹⁹ Be
0 3	1 3	2 3	3 3	4 3	5 3	6 3	7 3	8 3	9 3	10 3	11 3	12 3	13 3	14 3	15 3
°Li	"Li	°Li	°Li	'Li	°Li	۴Li	"Li	"Li	¹² Li	"Li	'*Li	"Li	"Li	"Li	"Li
0 2	1 2	2 2	3 2	4 2	5 2	6 2 8	7 2	8 2	9 2	10 2	11 2	12 2	13 2	14 2	15 2
°He	He	THe	тне	°Не	'He	°Не	°He	""He	"He	""He	""He	'"He	""He	""He	"He
° 1 ¹ H	²H	2 1 ³ H	³ 1 ⁴ H	4 1 ⁵ H	5 1 ⁶ H	6 1 ⁷ H	7 1 ⁸ H	⁸ 1 ⁹ H	⁹ 1	¹⁰ 1	¹¹ 1	¹² 1	¹³ 1	¹⁴ 1	¹⁵ 1

mantle

H burning shell

He core

The key parameter that drives the evolution in He burning is the He core mass and NOT the total mass

Central He burning always occurs in a convective environment



mantle

H burning shell

He core



S-process nucleosynthesis (weak component)



At the central He exhaustion we do not have any more a monoparametric family of stars but a Bi-parametric family.

In fact from now on there are two leading parameters that drive the further evolution of each star:



the CO core mass and the amount of C left by the He burning.

At the central He exhaustion we do not have any more a monoparametric family of stars but a Bi-parametric family.

In fact from now on there are two leading parameters that drive the further evolution of each star:

the CO core mass and the amount of C left by the He burning.





Let us discuss the advanced phases of massive stars first

EVOLUTION OF MASSIVE STARS

R. J. TAYLER* Princeton University Observatory Received March 15, 1954

ABSTRACT

The evolution is considered of massive stars with opacity due to electron scattering. As the stars evolve, the convective core retreats, and a zone of continuously varying composition is set up between the core and the envelope. Ten models have been obtained with core hydrogen content changing from 100 to 6 per cent. The evolutionary tracks of the models have been plotted in the H-R diagram. It is found that, although the individual tracks are very different from those found by other authors, the H-R diagram for stars of different masses but of the same age exhibits the well-known "knee," which occurs at the point of 11 per cent over-all reduction of hydrogen content.

I. INTRODUCTION

The course of stellar evolution is largely determined by the existence or nonexistence of general mixing currents in stellar interiors. If there are efficient mixing currents, a star



Alice crosses the mirror

neutrino energy losses



Pair neutrinos





C burning





Massive Stars: Carbon Burning



	$L =>$ total luminosity: $L_{\gamma} + L_{\nu}$											
M=80 M _o t = E / L(10 ⁶)	Мсс	Estimated lifetime	Real lifetime	Revised lifetime	L _{TOT}							
н=>не 6.44 10 ¹⁸ erg gr ⁻¹	60	6 10 ⁶	3.2 10 ⁶		10 ⁶							
He=>C	20	2 10 ⁵	3.3 10 ⁵		10 ⁶							
C=>Ne 1.85 10 ¹⁷ erg gr ⁻¹	1.5	4.5 10 ³	4.7 10 ²	4.5 10 ²	10 ⁷							
o=>si	1	4.8 10 ³	4.6 10 -2	4.8 10 -2	10 ¹¹							
si=>Ni 1.88 10 ¹⁷ erg gr ⁻¹	1	3.1 10 ³	4.3 10 ⁻³	3.1 10 ⁻³	10 ¹²							





Ne burning



Massive Stars: Oxygen Burning

The most abundant nuclei left by the Ne burning are: ¹⁶O, ²⁴Mg, ²⁸Si



O burning



Massive Stars: Carbon Burning



The advanced burning



The final compactness



												^{12 20} ³² Ca	¹³ 20 ³³ Ca	¹⁴ 20 ³⁴ Ca	^{15 20} ³⁵ Ca	^{16 20} ³⁶ Ca	¹⁷ 20 ³⁷ Ca	¹⁸ 20 ³⁸ Ca	^{19 20} ³⁹ Ca	²⁰ 20 ⁴⁰ Ca	²¹ 20	²² 20 ⁴² Ca	²³ 20
	O burning									¹⁰ ¹⁹	¹¹ ¹⁹ ³⁰ K	¹² 19	¹³ 19 ³² K	¹⁴ 19 ³³ K	¹⁵ 19 ³⁴ K	¹⁶ 19	¹⁷ 19 ³⁶ K	¹⁸ 19 ³⁷ K	К	^{20 19}	²¹ ¹⁹	²² 19 ⁴¹ K	²³ 19 ⁴² K
		lo n	hote	odici	into	arat	ion	Ar	9 18 27Ar	¹⁰ 18 ²⁸ Ar	^{11 18} ²⁹ Ar	^{12 18} ³⁰ Ar	^{13 18} ³¹ Ar	¹⁴ 18 ³² Ar	^{15 18} ³³ Ar	¹⁶ ³⁴ Ar	Ar	¹⁸ 18	¹⁹ 18 ³⁷ Ar	^{20 18} ³⁸ Ar	²¹ 18 ³⁹ Ar	²² 18 ⁴⁰ Ar	²³ 18 ⁴¹ Ar
											¹¹ ¹⁷ ²⁸ Cl	¹² 17 ²⁹ Cl	¹³ 17 ³⁰ Cl	¹⁴ 17 ³¹ CI	¹⁵ 17 ³² Cl	¹⁶ ³³ Cl	CI	¹⁸ 17 ³⁵ Cl	¹⁹ 17 ³⁶ Cl	²⁰ 17 ³⁷ Cl	²¹ ¹⁷ ³⁸ Cl	²² 17 ³⁹ Cl	²³ 17 ⁴⁰ Cl
				C bu	Irn			6	9 16 ²⁵ S	¹⁰ 16 26S	¹¹ ¹⁶ ²⁷ S	¹² 16 28S	¹³ 16 ²⁹ S	¹⁴ ³⁰ S	S	¹⁶ 16	¹⁷ 16 ³³ S	¹⁸ 16	¹⁹ 16 ³⁵ S	²⁰ 16	²¹ ¹⁶ ³⁷ S	²² 16 ³⁸ S	²³ ¹⁶
			н	le b	urn			15	9 15 ²⁴ P	¹⁰ ¹⁵	¹¹ ¹⁵ ²⁶ P	¹² 15	¹³ ¹⁵ ²⁸ P	¹⁴ 1 ²⁹ P	Ρ	¹⁶ 15	¹⁷ ¹⁵ ³² P	¹⁸ 15	¹⁹ 15	²⁰ ¹⁵ ³⁵ P	²¹ ¹⁵ ³⁶ P	²² 15 ³⁷ P	²³ 15
				¹⁸ Si	¹⁹ Si	²⁰ Si	²¹ Si	²² Si	9 14 ²³ Si	¹⁰ ¹⁴ ²⁴ Si	¹¹ ¹⁴ ²⁵ Si	¹² 1 ²⁶ Si	Si	Si	⁵ 14 ²⁹ Si	¹⁶ 14 ³⁰ Si	¹⁷ ¹⁴ ³¹ Si	¹⁸ ¹⁴ ³² Si	¹⁹ 14 ³³ Si	²⁰ 14 ³⁴ Si	²¹ ¹⁴ ³⁵ Si	²² 14 ³⁶ Si	²³ 14 ³⁷ Si
				4 13 ¹⁷ Al	⁵ 13	⁶ ¹³	⁷ 13 20AI	⁸ ¹³ ²¹ Al	⁹ ¹³ ²² Al	¹⁰ 13 ²³ Al	¹¹ ¹³ ²⁴ Al	¹² ²⁵ Al	AI	¹⁴ ¹³ ²⁷ Al	¹⁵ 13 ²⁸ Al	¹⁶ ¹³ ²⁹ Al	¹⁷ ¹³ ³⁰ Al	¹⁸ ¹³ ³¹ Al	¹⁹ ¹³ ³² AI	²⁰ 13 ³³ AI	²¹ ¹³ ³⁴ Al	²² ¹³ ³⁵ Al	²³ ¹³ ³⁶ Al
		² ¹² ¹⁴ Mg	³ 12 ¹⁵ Mg	⁴ 12 ¹⁶ Mg	⁵ 12 ¹⁷ Mg	⁶ ¹²	⁷ 12 ¹⁹ Mg	⁸ 12 ²⁰ Mg	9 12 ²¹ Mg	10 22	Иg	M	g g	¹⁴ 12 ²⁶ Mg	¹⁵ 12 ²⁷ Mg	¹⁶ 12 ²⁸ Mg	¹⁷ 12 ²⁹ Mg	¹⁸ 12 ³⁰ Mg	¹⁹ 12 ³¹ Mg	²⁰ 12 ³² Mg	²¹ 12 ³³ Mg	²² 12 ³⁴ Mg	²³ 12 ³⁵ Mg
		² 11 ¹³ Na	^{3 11} ¹⁴ Na	⁴ 11 ¹⁵ Na	⁵ 11 ¹⁶ Na	⁶ 11 ¹⁷ Na	⁷ 11 ¹⁸ Na	⁸ 11 ¹⁹ Na	9 11 ²⁰ Na	10 21	Na	¹² 11 ²³ Na	¹³ 11 ²⁴ Na	¹⁴ 11 ²⁵ Na	¹⁵ 11 ²⁶ Na	¹⁶ 11 ²⁷ Na	¹⁷ 11 ²⁸ Na	¹⁸ 11 ²⁹ Na	¹⁹ Na	²⁰ 11 ³¹ Na	²¹ 11 ³² Na	²² 11 ³³ Na	
°Ne	¹ ¹⁰ Ne	² ¹⁰ ¹² Ne	^{3 10} ¹³ Ne	⁴ ¹⁰ ¹⁴ Ne	^{5 10} ¹⁵ Ne	^{6 10}	^{7 10} ¹⁷ Ne	⁸ Ne	Ne	[%] Ne	²¹ Ne	¹² 10	¹³ 10 ²³ Ne	¹⁴ 10 ²⁴ Ne	¹⁵ 10 ²⁵ Ne	¹⁶ 10 ²⁶ Ne	¹⁷ 10 ²⁷ Ne	¹⁸ Ne	¹⁹ 10 ²⁹ Ne	²⁰ 10 ³⁰ Ne	²¹ 10 ³¹ Ne	²² 10 ³² Ne	
۴	¹ 9	2 9 ¹¹ F	³ 9	⁴ 9 ¹³ F	^{5 9}	⁶ 9	⁷⁹	89 17F	9 9 ¹⁸ F	¹⁰ ⁹	¹¹ 9	¹² 9 ²¹ F	¹³ 9 ²² F	¹⁴ 9 ²³ F	¹⁵ 9 ²⁴ F	¹⁶ 9 ²⁵ F	¹⁷ 9 ²⁶ F	¹⁸ 9 ²⁷ F	^{19 9}	²⁰ 9 ²⁹ F			
0	90	² 8 ¹⁰ O	³ 8 ¹¹ 0	4 8 ¹² O	⁵ 8 ¹³ O	⁶ 8 ¹⁴ O	7 150	0	°°° 170	¹⁰ ⁸	¹¹ 8 ¹⁹ O	¹² 8 20 <mark>0</mark>	¹³ 8 ²¹ O	¹⁴ 8 ²² O	¹⁵ 8 ²³ O	¹⁶ 8 ²⁴ O	¹⁷ 8 25 <mark>0</mark>	¹⁸ 8 ²⁶ O	¹⁹ 8 ²⁷ O	²⁰ 8 ²⁸ O			
'N	1 7 ⁸ N	2 7 ⁹ N	³⁷ ¹⁰ N	4 7 ¹¹ N	⁵⁷	⁶⁷	7 7 ¹⁴ N	⁸⁷	9 7 ¹⁶ N	¹⁰ 7 ¹⁷ N	¹¹ 7 ¹⁸ N	¹² 7 ¹⁹ N	¹³ 7 ²⁰ N	¹⁴ 7 ²¹ N	¹⁵ 7 ²² N	¹⁶ 7 ²³ N	¹⁷ 7 ²⁴ N	¹⁸ 7 ²⁵ N					
Ċ	¹ ⁶	² 6 ⁸ C	⁹ C	⁴ 6 ¹⁰ C	5 6 ¹¹ C	^{6 6}	7 6 ¹³ C	⁸⁶	^{9 6}	¹⁰ 6	¹¹ 6 ¹⁷ C	¹² 6 ¹⁸ C	¹³ 6 ¹⁹ C	¹⁴ 6 20C	¹⁵ 6 21C	¹⁶ 6 22C	¹⁷ 6 23C						
B	⁶ B	2 5 ⁷ B	^{з 5}	⁴ ⁵ ⁹ B	5 5 ¹⁰ B	^{6 5}	7 5 ¹² B	8 5 ¹³ B	9 5 ¹⁴ B	¹⁰ 5	¹¹ 5	¹² 5	¹³ 5	¹⁴ 5	¹⁵ 5 ²⁰ B	¹⁶ 5 ²¹ B							
Be	¹ 4 ⁵Be	2 4 ⁶ Be	^{3 4} ⁷ Be	* 4 *Be	⁵ ₄ ⁹ Be	^{6 4} ¹⁰ Be	7 4 ¹¹ Be	⁸⁴ ¹² Be	⁹⁴	¹⁰ 4	¹¹ 4 ¹⁵ Be	¹² 4 ¹⁶ Be	¹³ 4 ¹⁷ Be	¹⁴ 4 ¹⁸ Be	¹⁵ 4								
³Li	1 3 ⁴ Li	2 3 ⁵ Li	з з ⁶ Li	4 3 ⁷ Li	5 3 ⁸ Li	⁶³	7 3 ¹⁰ Li	8 3 ¹¹ Li	9 3 ¹² Li	¹⁰ 3	¹¹ 3	¹² 3	¹³ 3 ¹⁶ Li	¹⁴ 3 ¹⁷ Li									
He	¹ ² ³ He	² ² ⁴ He	³ ² ⁵ He	⁴ ² ⁶ He	⁵ 2 ⁷ He	⁶ ² ⁸ He	7 2 ⁹ He	⁸ 2 ¹⁰ He	⁹ 2 ¹¹ He	¹⁰ 2 ¹² He	¹¹ ² ¹³ He	¹² 2 ¹⁴ He											
H	1 1 ² H	2 1 ³ H	³ 1	4 1 ⁵ H	5 1 ⁶ H	6 1 ⁷ H	7 1 ⁸ H	8 1 ⁹ H	9 1 ¹⁰ H	¹⁰ 1	¹¹ 1												





												ep: 100.00%	ф: 100.00%	€ 100.00%	4. 100.00A	1.100.00.8	4. 100.00/4	4. 100.0024		
										36Sc	37\$c		395c <300 NS	40Sc 182.3 MS	41Sc 596.3 MS	42Sc 681.3 MS	43Sc 3.891 H	445c 3.97 H	A	46 83.3
			Ηbι	ırnin	g					р	р		P: 100.00%	€ 100.00% «p: 0.44%	€ 100.00%	€ 100.00%	€: 100.00%	€ 100.00%		β-:10
					0				34Ca <35 NS	35Ca 25.7 MS	36Ca 102 MS	37Ca 181.1 MS	38Ca 440 MS	39 Ca 859.6 MS	>7 40Ca	41Ca 1.02E+5 Y	4204	430	daCa .	45 162.
	6								Р	€ 100.00% ⊕ 95.70%	€ 100.00% Φ:54.30%	€ 100.00% ⊕: 82.10%	€:100.00%	€ 100.00%	$\mathbf{\mathbf{U}}$	€ 100.00%				β-: 1C
		/	нек	burni	ng			32K	33K <25 NS	34K <25 NS	35K 178 MS	36K 342 MS	37K 1.226 S	38K 7.636 M	801	1		42K 12.321 H	43K 22.3 H	44
								Р	Р	Р	< 100.00%	€ 100.00% (b) 0.05%	€: 100.00%	€ 100.00%		P IN TON		β-: 100.00%	β-: 100.00%	β-: 1C
			He s	hell	burn	ing	30Ar <20 NS	31Ar 14.4 MS	32Ar 98 MS	33Ar 173.0 MS	34Ar 844 5 MS	35Ar 1.775 S	3647	37Ar 34.95 D		39Ar 269 Y	40.1-	41Ar 109.61 M	42Ar 32.9 Y	43
							р	< 100.00%	< 100.00%	<: 100.00%	€ 100.00%	e: 100.00%		€ 100.00%		β-: 100.00%		β-: 100.00%	β-: 100.00%	β-: 1C
			C h.		_	28 CI	2901 <20 NS	30 C1	31Cl 150 MS	32C1 298 MS	33CI 2 511 S	34CI 1.5264.5	35/1	36C1 3.01E+5.Y		38CI 37.24 M	39C1	40Cl 1.35 M	41Cl 38.4.5	42
			Cbu	Irnin	g	Р	P	P	c 100.00%	€ 100.00%	€ 100.00%	€ 100.00%		\$-:98.10%		8-: 100.00%	β-: 100.00%	β-: 100.00%	8-: 100.00%	β-:1C
	_				265	275	285	295	0:0.70% 30S	31S	-	395	-	355 87.61.D		375 5.05 M	385	395	405	4
			O bi	urnin	g 2P	€ 100.00%	€: 100.00%	€ 100.00%	€ 100.00%	€: 100.00%				β-: 100.00%		8-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 10
				24P	25P	ф: 2.30% 26P	ер:20.70% 27Р	ф: 47.00% 28Р	29P	30P	210	32P	33P	34P	35P	36P	37P	38P	39P	40
				р	<30 NS	43.7 MS	€ 100.00%	< 100.00%	4.142 S	€ 100.00%		14.262 D β-: 100.00%	\$-: 100.00%	12.43 S β-: 100.00%	47.35 β-: 100.00%	\$-: 100.00%	2.31 S β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 10
			2251	* 2301	24.81	Ф 2551	q: 0.07% 2651	(p: 1.3E-3%) 27%	29.0	20.01	200	3151	3251	33%	3451	3551	3651	β-в: 12.00% 37Si	β-n: 26.00% 38.5i	β-n: 1 38
			29 MS	42.3 MS	140 MS	220 MS	2.234 S	4.16 S				157.3 M	153 Y	6.11 S	2.77 S	0.78 \$	0.45 S	90 MS 8-: 100.00%	>1 µS 8-n	47.
			(p: 32.00%) 21Al	ф: 71.00% 22A1	4p: 38.00% 23A1	49 24A1	25A1	26A1	2241	28A1	29A1	30A1	31Al	32A1	SBAI	34A1	β-n < 10.00% 35A1	β-n: 17.00% 36Å1	β- 37A1	38
			<35 NS	59 MS	470 MS	2.053 \$	7.183 \$	7.17E+5 Y		2.2414 M	6.56 M	3.60 S	644 MS	33 MS	41.7 MS	42 MS	38.6 MS	90 MS	10.7 MS	7.6
		19Mg	20Me	4p = 60.00%	(p: 0.46%	ed: 0.04%	24144	2514	2004	27Mg	28Mg	29Mz	30Mz	31Mg	β-h: 8.50%	8-n:27.00%	β-h: 41.00%	β-n < 31.00%	345Ma	37
			90.8 MS	122 MS	3.8755 \$	11.317 \$				9.458 M	20 915 H	1.30 5	335 MS	230 MS	86 MS	90.5 MS	20 MS	70 MS	3.9 MS	>26
		28	фs 27.00%	ф: 32.60%	<. 100.00%	0.100.00%	-	2000	2524	p 100.00%	p-: 100.0004	p-: 100.00%	p-: 100.00%	β-n: 1.70%	β-h 5.50%	β-n: 17.00%	β-1100.000%	β-h: 52.00%	β-h	p-: 10
		1 3E-21 S	<40 NS	447.9 MS	22.49 S	2.6027 Y		14.997 H	59.1 S	1.077 S	301 MS	30.5 MS	44.9 MS	48 MS	17.0 MS	13.2 MS	8.1 MS	5.5 MS	1.5 MS	
		P	Р	e: 100.00% er: 20.05%	€ 100.00%	€ 100.00%		β-: 100.00%	β-: 100.00%	\$-:100.00%	β-: 100.00% β-n: 0.13%	β-: 100.00% β-n: 0.58%	β-: 100.00% β-n: 21.50%	β-: 100.00% β-π: 30.00%	β-: 100.00% β-a: 37.00%	β-: 100.00% β-π: 24.00%	β-: 100.00% β-h: 47.00%	β-: 100.00% β-πs 100.00%	β-: 100.00% β-h	
	16Ne 122 KeV	17Ne 109.2 MS	18Ne 1672 MS	19Ne 17.22 S	24			23Ne 37.24 S	24Ne 3.38 M	25Ne 602 MS	26Ne 192 MS	27Ne 32 MS	200Ne 19 MS	25Ne 15.6 MS	30Ne 7 MS	31Ne 3.4 MS	32Ne 3.5 MS		34Ne >60 NS	
	P: 100.00%	€ 100.00% Ф≈ 100.00%	e: 100.00%	€ 100.00%			$\overline{}$	β-: 100.00%	β-: 100.00%	\$-:100.00%	$\begin{array}{c} \beta \text{-:} \ 100.00\% \\ \beta \text{-tt} \ll 0.2\% \end{array}$	β-: 100.00% β-n: 2.00%	β-: 100.00% β-n: 16.00%	β-: 100.00% β-π: 17.00%	β-: 100.00% β-h = 26.00%	β-: 100.00% β-h	β-: 100.00%		β- β-m	
	15F 1.0 MeV	16F 40 KeV	17F 64.49 S	18F 1.8291 H	108	20F 11.07 S	21F 4.158 S	22F 4.23 S	23F 2.23 S	24F 390 MS	25F SO MS	26F 9.6 MS	27F 5.0 MS	28F <40 NS	29F 2.5 MS	30F <260 NS	31F >250 NS			
	P: 100.00%	P. 100.00%	€ 100.00%	c 100.00%		β-: 100.00%	β-:100.00%	β-: 100.00% β-n < 11.00%	β-: 100.00%	$\begin{array}{l} \beta \! - \! : 100.00\% \\ \beta \! - \! h \ll 5.90\% \end{array}$	β-: 100.00% β-h: 14.00%	β-: 100.00% β-κ 11.00%	β-:100.00% β-h:77.00%	N	β-: 100.00% β-π: 100.00%	N	β- β-n			
	140 70.606 \$	150 122.24 S	150	170	180	190 26.88 S	200 13.51 S	210 3.42 S	220 2.25 \$	230 82 MS	240 65 MS	250 <50 NS	260 <40 NS	270 <260 NS	280 <100 NS					
٤	€ 100.00%	€: 100.00%				β~: 100.00%	β-:100.00%	β-: 100.00%	β-: 100.00% β-n < 22.00%	β-: 100.00% β-η: 31.00%	β-: 100.00% β-h: 58.00%	N	N	N	N					
	13N 9.965 M	1401	1 EM	16N 7.13 S	17N 4.173 S	18N 624 MS	19N 271 MS	20N 130 MS	21N 85 MS	22N 24 MS	23N 14.5 MS	24N <52 NS	25N <260 NS							
	€ 100.00%			β-: 100.00% β-σ: 1.2E-3%	β-: 100.00% β-π: 95.1%	β-: 100.00% β-π: 14.30%	β-: 100.00% β-π: 54.60%	β-: 100 00% β-π: 57 00%	β-: 100 00% β-π: 81 00%	β-: 100.00% β-π: 36.00%	β-: 100.00% β-π	N	N							
		120	14C 5700 Y	15C 2.449 S	16C 0.747 S	17C 193 MS	18C 92 MS	19°C 49 MS	20C 14 MS	21C <30 NS	22C 6.1 MS									
			β-: 100.00%	β-: 100.00%	β-: 100.00% β-h: 99.00%	β- 100.00% β-1:32.00%	β-: 100.00% β-n: 31.50%	β-n: 61.00% β-	β-: 100.00% β-b: 72.00%	N	β-: 100.00% β-h: 61.00%									
			100			1.00		100												



Beyond the O burning matter approaches progressively the Nuclear Statistical Equilibrium

At the central O exhaustion => $T \sim 2.5 \cdot 10^9 \text{ K}$ direct reverse $i + k \rightarrow j + l$ $j + l \rightarrow i + k$

 $R_{ik} \sim R_{jl}$

To quantify how close a pair of processes is to the equilibrium let us define a parameter φ :

 $arphi({f i},{f j})=rac{|{f r_{ij}}-{f r_{ji}}|}{\max({f r_{ij}},{f r_{ji}})}$ obviously $arphi
ightarrow {f 0}$ full equilibrium $arphi
ightarrow {f 1}$ no equilibrium

Beyond O burning...the path towards the Nuclear Startistical Equilibrium





N _

Nuclear Statistical Equilibrium

At T>5 GK full equilibrium between direct and reverse processes

 $(N,Z) \rightleftharpoons Zp + Nn$

$$\begin{split} \mathbf{y}_{i(\mathbf{Z},\mathbf{N})} &= \omega(\mathbf{z},\mathbf{n}) \left(\rho \mathbf{N}_{\mathbf{A}}\right)^{\mathbf{A}-1} \left(\frac{\mathbf{A}\mathbf{m}_{\mathbf{p}}\mathbf{k}\mathbf{T}}{2\pi\hbar^{2}}\right)^{3/2} \mathbf{y}_{\mathbf{p}}^{\mathbf{z}} \mathbf{y}_{\mathbf{n}}^{\mathbf{n}} 2^{-\mathbf{A}} \left(\frac{2\pi\hbar^{2}}{\mathbf{m}_{\mathbf{p}}\mathbf{k}\mathbf{T}}\right)^{\mathbf{A}\frac{3}{2}} \mathrm{e}^{-\frac{\mathbf{Q}(\mathbf{z},\mathbf{n})}{\mathbf{k}\mathbf{T}}} \\ \mathbf{y}_{i(\mathbf{Z},\mathbf{N})} &= f(\mathbf{A},\mathbf{T},\rho) \mathbf{y}_{\mathbf{p}}^{\mathbf{z}} \mathbf{y}_{\mathbf{n}}^{\mathbf{n}} \mathbf{e}^{-\frac{\mathbf{Q}(\mathbf{z},\mathbf{n})}{\mathbf{k}\mathbf{T}}} \end{split}$$

Nuclear Statistical Equilibrium

								Р	р	р	р	e: 100.00%	e: 100.00%	€: 100.00%	€: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	elle de la constante de la cons
							58Ge	59 Ge	60 Ge ≈ 30 MS	61Ge 39 MS	62Ge 129 MS	63Ge 142 MS	64Ge 63.7 S	65Ge 30.9 S	66Ge 2.26 H	67Ge 18.9 M	68Ge 270.95 D	69 Ge 39.05 H	70Ge STABLE	7
							2P	2P	2P	e: 100.00%	÷	e: 100.00%	e: 100.00%	€ 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	20.37%	e <mark>n</mark>
						56Ga	57Ga	58Ga	59 Ga	60 Ga 70 MS	61Ga 168 MS	62Ga 116.10 M ^c	63Ga 32.4 S	64Ga 2.627 M	65Ga 15.2 M	66Ga 9.49 H	67Ga 3.2617 D	68Ga 67.71 M	69 Ga STABLE	7 21
						р	Р	Р	Р	e: 98.40% sb: 1.60%	e: 100.00%	129,00%	«: 100.00%	< 10 10 ms	e: 100.00%	e: 100.00%	e: 100.00%	e: 100.00%	60.108%	Bog and a second se
					54Zn	552n >0.5 μS	562n >0.5 μS	57Zn 38 MS	58Zn 84 MS	59Zn 182.0 MS	60Zn 2.38 M	61Zn 89.1 S	62Zn 9.186 I	7.52n 29.47 M	64Zn STABLE	65Zn 243.66 D	662n STABLE	67Zn STABLE	682n STABLE	6 54
					2P	P ¢	P	€ 100.00% (p≥ 65.00%	«: 100.00%	e: 100.00% sp: 0.10%	e: 100 x 7%	e: 100.00%	€ 100 J0%	€: 100.00%	48.63%	e: 100.00%	27.90%	4.10%	18.75%	β-:1
				52Cu	53Cu <300 NS	54Cu <75 NS	55Cu >200 NS	56Cu 94 MS	57Cu 196.3 MS	58Cu 3.204	59Cu 81.5 S	60Cu 23.7 M	61.0u 3.333 H	62Cu 9.67 M	STABLE	64Cu 12.7C H	65Cu STABLE	66Cu 5.120 M	67Cu 61.83 H	6 3
				Р	P ¢	Р	e: 100.00%		e: 100.00%	e: .00%	e: 100.00%	e: 10	e: 100.00%	€: 100.6.5%	• 69.17%	61.5.% 6-1.78.00%	30.83%	β-: 100.00%	β-: 100.00%	β-:1
	48Ni >0.5 μS	49Ni 12 MS	50Ni 12 MS	51Ni >200 NS	52Ni 38 MS	53Mi 45 MS	54Ni 104 MS	55Ni 202 MS	6.075	57Ni 35.60 H	STAR	59Ni 7.6E+4 Y	60Ni STABLE	GANI STABLE	62Ni STABLE	03Ni 100.1 Y	64Ni STABLE	65Ni 2.5172 H	66Ni 54.6 H	
	•	€: 100.00% €₽	ф: 70.00% б		€ 100.00% «p: 17.00%	€: 100.00% €p.:: 45.00%	e: 100.00%	e: 100.00%	V	e: 100.00%		e: 100.00%	26.223%	1.140%	3.80	β-: 100.00%	0.926%	β-: 100.00%	β-: 100.00%	β-:1
			49Co <35 NS	50Co 44 MS	51Co >200 NS	52Co 115 MS	53Co 240 MS	54Co 193.27 _3	55Co 17.53 H	56Co 77.231	57Co 271.74 D	58Co 70.86 P	59Co STABLE	60Co 1925.2F	61Co 1.650 H	62Co 1.50 M	63Co 27.4 S	64Co 0.30 S	65Co 1.20 S	
			P 4	€ 100.00% (p > 54.00%)		€ 100.00%	e: 100.00%	J0.00%	e: 100.00%	J.00%	e: 100.00%	e: 17	100%	β-1 .00%	β~: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	p-:1
ISFe .8 MS	46Fe 12 MS	47Fe 21.8 MS	48Fe 44 MS	49Fe 70 MS	SOFe 155 MS	51Fe 305 MS	52Fe 8.27 .1	53Fe 8.51 M	67	55Fe 2.737 Y	STAB	57Fe STABLE	STAP	59Fe 44.495 D	60Fe 1.5E+6 Y	61Fe 5.98 M	62Fe 68 S	63Fe 6.1 S	64Fe 2.0 S	
2P		€: 100.00% ¢p > 0.00%	€ 100.00% (p ≥ 3.60%	€: 100.00% «p ≥ 52.00%	€: 100.00% «p≈ 0.00%	€: 100.00%	, JO.00%	e: 100.00%		e: 100.00%		2.119%		β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	<mark>β-:1</mark>
4Mn .05 NS	45Mn <70 NS	46Mn 34 MS	47Mn 100 MS	48Mn 158.1 MS	49Mn 382 MS	50M 283 / MS	51Mn 46.2 M	52M 5.5 0	53Mn 3.74E+6 Y	54Mn 312.17	55Mn STABLE	56Mn 2.578	57Mn 85.4 S	58Mn 3.0 S	59Mn 4.59 S	60Mn 51 S	61Mn 0.67 S	62Mn 671 MS	63Mn 0.29 S	6 9
é P	Р	e: 100.00% sp: 22.00%	€: 100.00% «p ≥ 3.40%	e: 100.00% sp: 0.28%	e: 100.00%	+00.00%	e: 100.00%	,100.00%	€ 100.00%	* .00% 2.9E-4%	100%	P .J0.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β100.00%	8-: 100.00%	8-100.00%	8-100.00%	8-1
IBCr .6 MS	44Cr 53 MS	45Cr 50 MS	46Cr 0.26 S	47 Cr 500 MS	480 21 H	49Cr 42.3 M	50Cr >1.3E+18 Y	51Cr 27.7025 D	STAT	53Cr STABLE	ST .	55Cr 3.497 M	56Cr 5.94 M	57Cr 21.1 S	58Cr 7.0 S		0			
00.00% 23.00%	€ 100.00% ¢p > 7.00%	€ 100.00% ¢p > 27.00%	€ 100.00%	€ 100.00%	100.00%	€ 100.00%	24	e: 100.00%		9.501%		β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β	0.5	1		
42V 55 NS	43V >800 MS	44V 111 MS	45V 547 MS	46" 42" MS	47V 32.6 M	48V 15.9735 D	49V 329 D	50V 1.4E- f	51V STABLE	52V 3.7 A	53V 1.60 M	54V 49.8 S	55V 6.54 S	56V 216 MS	57V 0.35 S		-1			
Р	€ 100.00%	e: 100.00% ed	€ 100.00%	100.00%	e: 100.00%	e: 100.00%	e: 100.00%	.3.00% -: 17.00%	88.1 55N	400.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	$\substack{\beta=:100.00\%\\\beta=h:0.04\%}$	β-	15			
11Ti 0.4 MS	42Ti 199 MS	43Ti 509 MS	44Ti 60.0 Y	45Ti 184.8 M	46Ti STABLE 8 25%	47Ti STABLE 7.44%	48D ST	49Ti STABLE 5.41%	507 ST LE	51Ti 5.76 M	52Ti 1.7 M	53Ti 32.7 S	54Ti 1.5 S	55Ti 1.3 S	56Ti 200 MS	X	1.5			
100.00% 00.00%	€ 100.00%	e: 100.00%	€ 100.00%	«: 100.00%	0.2074					β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	$\begin{array}{c} \beta \text{-:} 100.00\% \\ \beta \text{-n} \end{array}$	OB10	-2			
IOSe 2.3 MS	41Sc 596.3 MS	42Se 681.3 MS	43Sc 3.891 H	44Sc 3.97 H	45Sc STABLE 100%	465c 83.79 D	475c 3.3492 D	485c 43.67 H	495c 57.2 M	50Sc 102.5 S	51Sc 12.4 S	52Sc 8.2 S	53Sc >3 S	54Sc 0.36 S	55Sc 0.115 S		2.5			
00.00%	€ 100.00%	€ 100.00%	€ 100.00%	«: 100.00%		β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00% β-n	β-: 100.00%	$\begin{array}{c} \beta \text{-:} 100.00\% \\ \beta \text{-n} \end{array}$		-3			
9Ca 9.6 MS	40Ca >3.0E+21 ¥ 96.94%	41Ca 1.02E+5 Y	42Ca STABLE 0.647%	43Ca STABLE 0.135%	44Ca STABLE 2 09%	45Ca 162.61 D	46Ca >0.28E+16 Y 0.004%	47Ca 4.536 D	48Ca 2.3E19 Y 0.187%	49Ca 8.718 M	50Ca 13.9 S	51Ca 10.0 S	52Ca 4.6 S	53Ca 90 MS	54Ca >300 NS	>	-5			
00.00%	24	«: 100.00%				β-: 100.00%	2β-	β-: 100.00%	2β-:84.00% β- <25.00%	β-: 100.00%	β-: 100.00%	$\begin{array}{c} \beta \text{-:} 100.00\% \\ \beta \text{-n} \end{array}$	β-: 100.00% β-ns 2.00%	β -: 100.00% β -n > 30.00%	β-: 100.00%	-	3.5			
38K	39K	40K	41K	42K	43K	44K	45K	46K	47K	48K	49K	50K	51K	52K	53K		-4			
																	0.44		0.45	0.46 0.47 0.48 0.49 0.50 Ye
																			Ni58	—Ni56 —Fe58 —Fe56 —Fe54 —Cr54 —Cr52

Nuclear Statistical Equilibrium






Total amount of energy released by the gravitational collapse amounts to, roughly: ${ m E}=1.6~10^{53}~{ m erg}$



Total amount of energy released by the gravitational collapse amounts to, roughly:

${ m E}=1.6\,\,10^{53}\,\,{ m erg}$

Table 2. For the runs presented in this paper, the mean shock radius (in units of 1000 kilometres) and mean shock speed (in units of 1000 km s^{-1}) at the end of each simulation. Note that the shock is still stalled at the end of the simulation only for the 2D and 3D $13-M_{\odot}$ models.

	t (final) (s)	Mean shock radius (1000 km)	Mean shock speed (1000 km s^{-1})
s9.0-2D	1.41	15.24	14.19
s9.0-3D	1.042	12.42	16.29
s10.0-2D	1.41	7.70	10.62
s10.0-3D	0.767	1.96	6.65
s11.0-2D	1.41	9.18	7.41
s11.0-3D	0.568	2.75	8.00
s12.0-2D	1.41	8.72	8.08
s12.0-3D	0.694	2.66	6.85
s13.0-2D	1.311	0.06	0.067
s13.0-3D	0.674	0.09	0.048



Burrows+ (2019) MNRAS 485, 3168



















NSE: all nuclei are at the equilibrium Complete Explosive Silicon burning





QSE: ²⁸Si is not ad the equilibrium Incomplete Explosive Silicon burning

 $Y_i = f(T, \rho, Y_e)$

V Cr Mn Si S Ar Ca

 $4 \cdot 10^9 \ {\rm K} \ > \ T \ > \ 3.3 \cdot 10^9 \ {\rm K}$

2QSE: matter clustered in two groups, one peaked at ²⁸Si (99%) and the second one at Fe Explosive Oxygen burning

Si S Ar K Ca

 $3.3 \cdot 10^9 \mathrm{~K} > T > 1.9 \cdot 10^9 \mathrm{~K}$

Explosive Neon and Carbon + C shell burning

Ne Na Mg Al P Cl



NO Explosive burning

Element	produced	destroyed
He (⁴He)	H _{c,s}	He _{c,s}
C (¹² C)	He _{c,s}	C _{c,s}
N (¹⁴ N)	H _{c,s}	He _{c,s}
O(¹⁶ O)	He _c	C _{c,s}
F (¹⁹ F)	Hes	
Ne (²⁰ Ne)	C _s	Ne _x
Na (²³ Na)	C _s	Ne _x
Mg (²⁴ Mg)	C _s	Ne _x
AI (²⁷ AI)	C _s	Ne _x
Si (²⁸ Si)	Si _{ix} O _x Ne _x	
P (³¹ P)	Ne _x C _s	Ne _x
S (³² S)	Si _{ix} O _x Ne _x	
Cl	³⁵ Cl O _x Ne _x - ³⁷ Cl C _s	³⁷ Cl Ne _x
Ar (³⁶ Ar)	Si _{ix} O _x	
K (³⁹ K)	He C _s O _x	0 _x
Ca (⁴⁰ Ca)	Si _{ix} O _x	

Element	produced	destroyed
V (⁵¹ V)	Si _{ix}	
Cr (⁵² Fe)	Si _{ix}	
Mn (55Fe 55Co)	Si _{ix}	
Sc (⁴⁵ Sc, ⁴⁵ Ca)	He C _s Si _x	Ne _x
Ti (⁴⁸ Cr)	O _x Si _x Si _{ix}	
Fe (⁵⁶ Ni ⁵⁶ Fe ⁵⁴ Fe)	Si _{ix} O _x	
Co (⁵⁹ Ni)	He _c Ne _x Si _x	
Ni (⁵⁸ Ni)	Si _x	
Cu(⁶³ Cu)	He _c Ne _x Si _x	
Zn(⁶⁴ Zn)	He _c Ne _x Si _x	

Solar metallicity



Production Factors produced by a generation of massive stars:





Element

Critical masses (model dependent)

H ignition (4P => ⁴ He)	0.07 M _☉	Low mass stars:	
He ignition (off center, degenerate)	0.5 M _☉ •	RGB He white dwarfs	
He ignition (central, not degenerate)	2.3 M _o	Intermediate mass stars:	
C ignition (off center, degenerate)	7.5 M _☉ ●	Thermally Pulsing stars CO white dwarfs	
C ignition (central, not degenerate)	8 M _o	ONe white dwarfs	
		top end of the TP stars	
Ne ignition (off center)	10 M _o	electron capture Supernovae ???	
	Ŭ		
Ne ignition (central)	11 M _o	Massive stars: Core collapse supernovae	
EOS dominated by e^+-e^- pairs ($\Gamma < 4/3$)	140? M		
	<u> </u>	(Pulsational) Pair instability supernovae	
	260? M _☉		